CHAPTER 8

Radio Telemetry as a Wildlife Research Tool

FREDERICK F. KNOWLTON

1995. Pages 81-106 *in* S. H. Berwick and V.B. Saharia. eds., The Development of International Principles and Practices of Wildlife Research and Management: Asian and American Approaches. Oxford University Press, Delhi. 481 pp.

Introduction

Radio telemetry is a relatively recent and exciting development in the study of wild animals. It was made practical as a result of several significant advances in the field of electronics, namely, the invention of transistors and integrated circuit chips. These inventions, which allowed miniaturization of amplifying and control circuits with low voltage requirements, resulted in the development of radio transmitters small enough to be carried by animals. Currently, simple transmitters small and light enough to be worn by field mice are in use as well as much more sophisticated systems, some transmitting physiologic information, some capable of operating for several years, and others that use satellites in their information-transfer system. In some aspects, radio telemetry may be approaching the limits of practicality, but in others, it is limited only by the ingenuity and imagination of the people applying it to the problems they wish to solve.

The following is not intended as an exhaustive treatment of the techniques and applications of radio telemetry to wildlife problems. Instead, it is meant to be a useful introduction for the novice, providing enough basic information to allow people to get an effective start with a minimum of trials, frustrations and failures.

Applications

Radio telemetry is one of many research tools. It can be helpful in answering some types of questions but may not be useful for others. The value it brings to problem-solving is directly related to the types of problems, or the relevance of the specific questions the wildlife biologist is asking. In this respect it is much like statistics, radioisotopy, surgical procedures, and a host of other techniques. Biologists become noted on the basis of the quality of the questions they seek to answer, not the equipment or techniques they use in the process of answering them. In this context, some general comments about radio telemetry may be helpful.

Radio telemetry is the process of creating, measuring and/or transferring 'information' from a source to a distant location via radio waves, which are a form of electromagnetic energy. In wildlife biology, it has been used in two primary applications: (1) to provide information about the location of animals that are not readily seen; and (2) to measure and transfer information about events at distant locations. In the first instance, a relatively simple radio transmitter or beacon placed on the animal provides a periodic signal which is transmitted in all directions. More sophisticated equipment or techniques are used at the receiving end to detect the direction from which the signal is coming. We should recognize two purposes for determining location: one is to describe the patterns in which animals use space: the other to identify and locate the same animals repeatedly so that other information may be collected, such as behavioural observations, recapture for a variety of purposes, indications of den location, etc. It is important to precisely identify our objectives because they could influence the type of equipment we might want to use.

The second primary application, that of measuring and transferring information to a distant location, is usually more complex. It can be relatively simple if it merely requires providing information about when an event occurs, which could be signalled merely by switching a transmitter on or off, but can become more complex where continuous reporting of environmental conditions via radio techniques is involved (e.g. some weather stations). Perhaps the most complex arrangements involve monitoring physiologic functions of free-ranging wild animals because both the transmitting and receiving equipment need to be relatively sophisticated. Biologists who think radio telemetry might be useful in their programmes, especially those just starting out, should carefully identify the questions they want to answer, the specific kinds of data they plan to collect, and how they plan to analyse that information before selecting the type of equipment to be used.

Much of the remaining discussion will concentrate on the use of telemetry as a means of locating animals because that currently encompasses 90 to 95 per cent of the current use of radio telemetry in wildlife biology. However, some discussion of more recent trends in wild animal telemetry is also included.

Some Preliminary Comments

I have no intention of embarking on an involved technical discussion of radio waves and propagation of radio transmission. But a cursory knowledge of the properties of radio waves will provide a firmer basis for understanding later discussions.

Radio waves are a form of electromagnetic energy which flows through space in an invisible sinusoidal wave form. It is a pulse of energy with very weak alternating positive and negative electrical charges (see Figure 1). Radio waves all travel at the same speed (30,000 km/second). They are designated by the *frequency*, or the number of complete oscillations they make each second. Another parameter of a radio wave is the *wavelength*, the physical distance between a specific point on one wave and the comparable point on the ensuing wave. Since all radio waves travel at the same speed, and the distance travelled by a radio wave is the product of the length and frequency of waves, there is

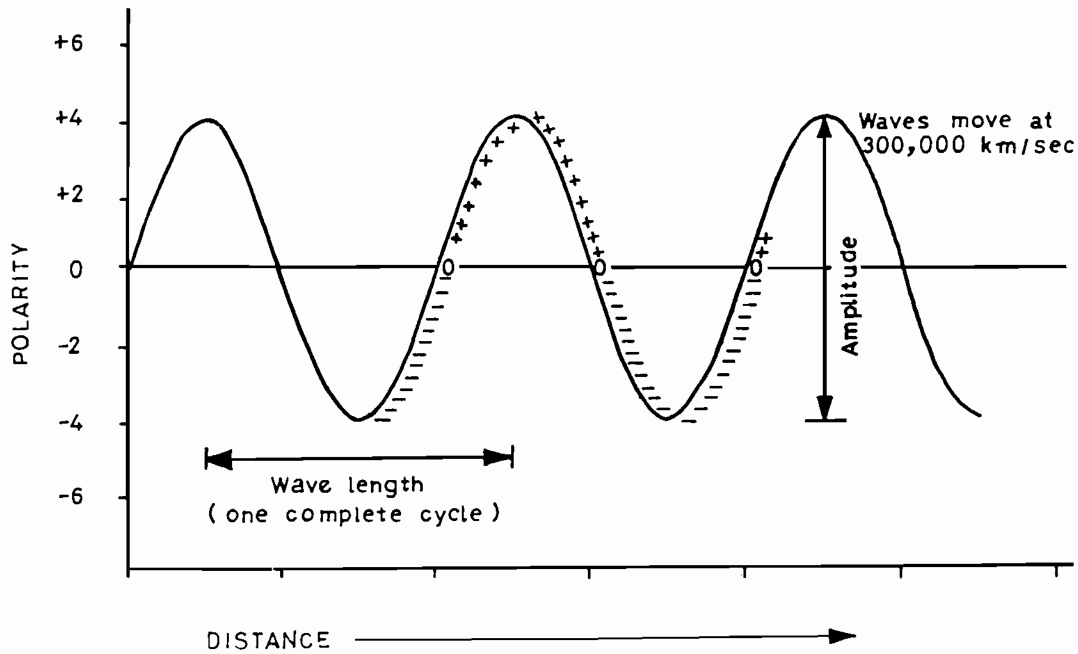

FIGURE 1. Diagrammatic representation of a radio wave showing two changes in polarity per cycle; frequency is the number of complete cycles, or waves, per sec-

an inverse relation between frequency and wavelength: as frequency increases, wavelength becomes shorter and vice versa. There are several practical aspects of this relationship:

1. A radio transmitter and a radio receiver must operate on the same frequency. Typically each transmitter used in wildlife telemetry operates on a single frequency while most receivers are set up to operate over a series of closely related frequencies.
2. The differences in electrical potential (that is the differences between the positive and negative charges) that we are trying to detect are very small, usually in the range of a few microvolts. As result, the equipment we use in terms of receivers, antennas, and cables must be sensitive. We need to treat them appropriately to maintain that sensitivity.
3. The efficiency and sensitivity of an antenna, for either transmitting or receiving, is partially related to its dimensions relative to the wavelength or the frequency at which you are working. In general, the higher the frequency, the shorter the wavelength, and hence the dimensions of the antenna to achieve the same sensitivity.
4. Lower frequency radio waves typically are better at penetrating vegetation and/or at passing through or around topographic features than radio waves of higher frequencies.

The first two items above are rudimentary and mentioned to make certain we do not start off with any misconceptions. Items 3 and 4 start to identify some of the factors involved in the compromises associated with selecting a frequency around which to build a telemetry system. Since much of the current use of radio telemetry involves direction-finding, there is a premium upon antenna configurations which are physically small so that high gain (sensitive) antennas with acute directionality can be used. This suggests high frequency equipment. This option becomes somewhat less attractive, however, because you may sacrifice ability to 'penetrate' vegetation, increase the likelihood of 'bounce' (false identification of the point of origin of a signal), and have to accept an operational tendency toward line-of-sight reception capabilities at higher frequencies. Most telemetry groups operating in North America have resolved these compromises and operate between 140 and 175 megahertz (MHz). There are some special applications where individuals choose to work at 27–30 MHz or even at 220 MHz, but the majority of biologists are operating in the intermediate range mentioned. Before proceeding, I would encourage the novice to determine whether there are any governmental restrictions on the use of specific frequencies or whether perhaps specific frequencies are reserved for wild animal work. Such a check could protect investments in equipment, time, and animal handling.

Parts of a Radio Telemetry System

We should place the various components of a radio telemetry system in perspective before engaging in a detailed discussion of each of them.

A radio telemetry system has four essential components (Figure 2): (1) a radio signal source, usually called a transmitter; (2) a detector which commonly is composed of a receiving antenna and a radio receiver; (3) some sort of information output, which may be as simple as a speaker incorporated in the receiver which gives a tone or beep whenever a signal is received, or may be an infinitely modern complex computer printout of special information; and (4) some sort of interpretation formulated by a person. The latter might simply be the mental integration of relative signal strength and antenna position within a telemetrist's mind, or it might involve assimilation of complex mathematical or statistical computations concerning the information received. Without all four components, the system is not useful. We may now examine each of the components more closely.

The Radio Receiver

The radio reciever is the heart of any telemetry system. It is the most sophisticated and expensive individual component of a system; costs commonly run from US$ 600 to 1,600 for commercially available receivers. The numerous knobs, buttons, meters, gauges, receptacles and other accessories can create panic among the uninitiated. This need not be. Typically, there are only three types of components on the control panels of most telemetry receivers: (1) meters and gauges to tell how the receiver is adjusted or functioning; (2) receptacles for various types of input and output connectors; (3) switches and controls; and (4) perhaps some 'devices' that are not manipulated in routine receiver operations. The components that are commonly found on commercially available telemetry receivers are identified in Table 1 and Figure 3.

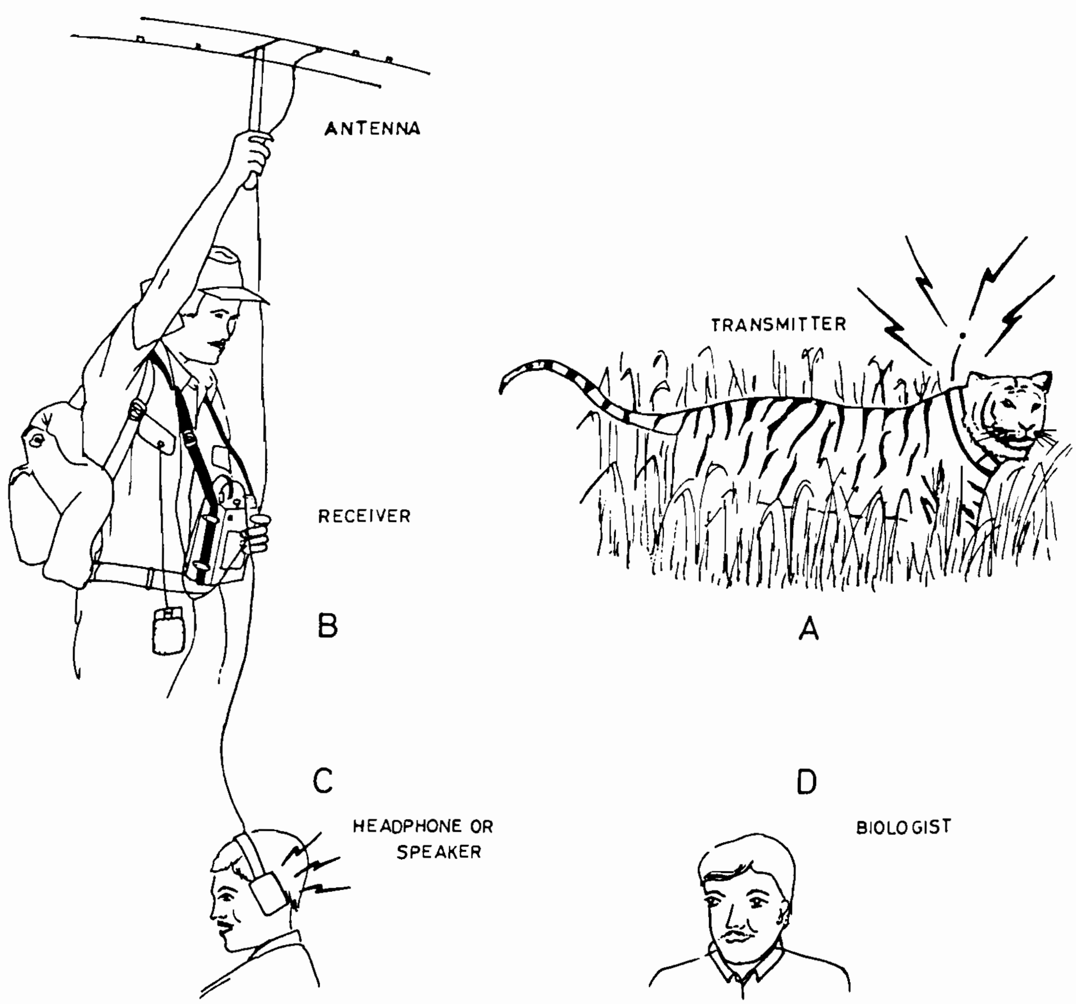

FIGURE 2. Diagrammatic representation of the major components of a telemetry system, including source (A), detector (B), information output (C), and interpretation

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TABLE 1. Components typically found on the control panels of commercial telemetry receivers

Component/Device	Description/Appearance	Remarks
A. METERS AND GAUGES		
1. Battery voltage meter	Usually a small red and green 'button' gauge with a deflection needle, but can involve signal strength meter coupled to a special switch.	Receiver usually must be turned on for voltmeter to register. Indicates when batteries need to be recharged or changed.
2. Signal strength meter	A moderate size voltmeter in which the pointing needle deflects in direct proportion to the amplitude of the signal and/or noise coming through the receiver.	These meters generally do not discriminate changes in a signal amplitude as well as does the human ear.
3. Channel or frequency indicator	Usually a series of numbers on or around a rotary stepswitch to indicate the general frequency (or channel) to which the receiver is tuned.	May be a single clock-type individual or a series of 2 or 3 'wheel indicators' in tandem.
4. Fine-tune indicator	Usually a series of marks or graduations surrounding a continuous action rotary knob.	Pointer is usually a mark or attachment to the knob itself. Indicates the precise frequency tuning of the receiver or position of the best frequency oscillator (BFO).
5. Gain control indicator	Similar to fine-tune indicator.	Indicates the relative amount of amplification the receiver is providing to the incoming signals.
B. CONNECTORS AND PLUGS		
6. Antenna Input	Usually a BNC-type single pin connector for coaxial cable. Collar of receptacle has two nubs of ears onto which the cable terminal locks.	Coaxial cable from antenna attaches and locks with a clockwise twisting motion.
7. External power plug	May be a single or double pin plug. If double pins, they will be coded by size or colour (black or red) to assure correct polarity.	Correct voltage must be assured to avoid burning out the receiver circuits. With appropriate transformers, commercial power source, vehicle power systems or large storage batteries can be used. Recharging appropriate internal batteries is achieved via this plug.
8. Earphone ports	One or two round receptacles for earphone jacks.	Earphone jacks will snap into correct position when inserted into the receptacle. Inserting earphone jack normally stops output to the speaker in the receiver.
9. Other output ports	Usually one or two round receptacles similar to those for earphones.	These are generally used to drive auxiliary meters, recording equipment, or measurement devices.
C. RECEIVER CONTROLS		
10. On-off power switch	Two or three-position toggle switch *or* extreme counterclockwise 'click' position of gain control knob.	Failure to turn off receiver will result in unnecessary battery drain and/or premature battery failure.
11. Gain control knob	Smooth action rotary knob typically increasing the amplitude of the receiver output as the knob is turned clockwise.	Main power switch may be incorporated as the extreme counterclockwise 'click' position of this knob.
12. Frequency (channel) selector	Multi-step rotary switch which snaps into specific position. May be single horizontal switch *or* 'gangs' of vertical rotary switches.	Tunes receiver by selecting one of a series of general frequency ranges or channels.
13. Fine-tune adjustment	A continuous smooth-action rotating knob.	Adjusts the receiver frequency tuning within a narrow band around the band selected by the frequency selector.
D. MISCELLANEOUS ITEMS		
14. Internal speaker	A small diaphragm or pin-hold device which produces audible receiver tones in the absence of earphones.	Internal speaker normally is automatically switched off when earphone jack is properly inserted in earphone receptacle.
15. Battery access port	Usually a small door held shut by screws *or* access by removing entire control panel and circuitry from receiver box.	Be aware whether specific receiver is using rechargeable or replaceable batteries. It is best to minimize need to expose receiver circuits to avoid damage and/or dust and dirt accumulations.

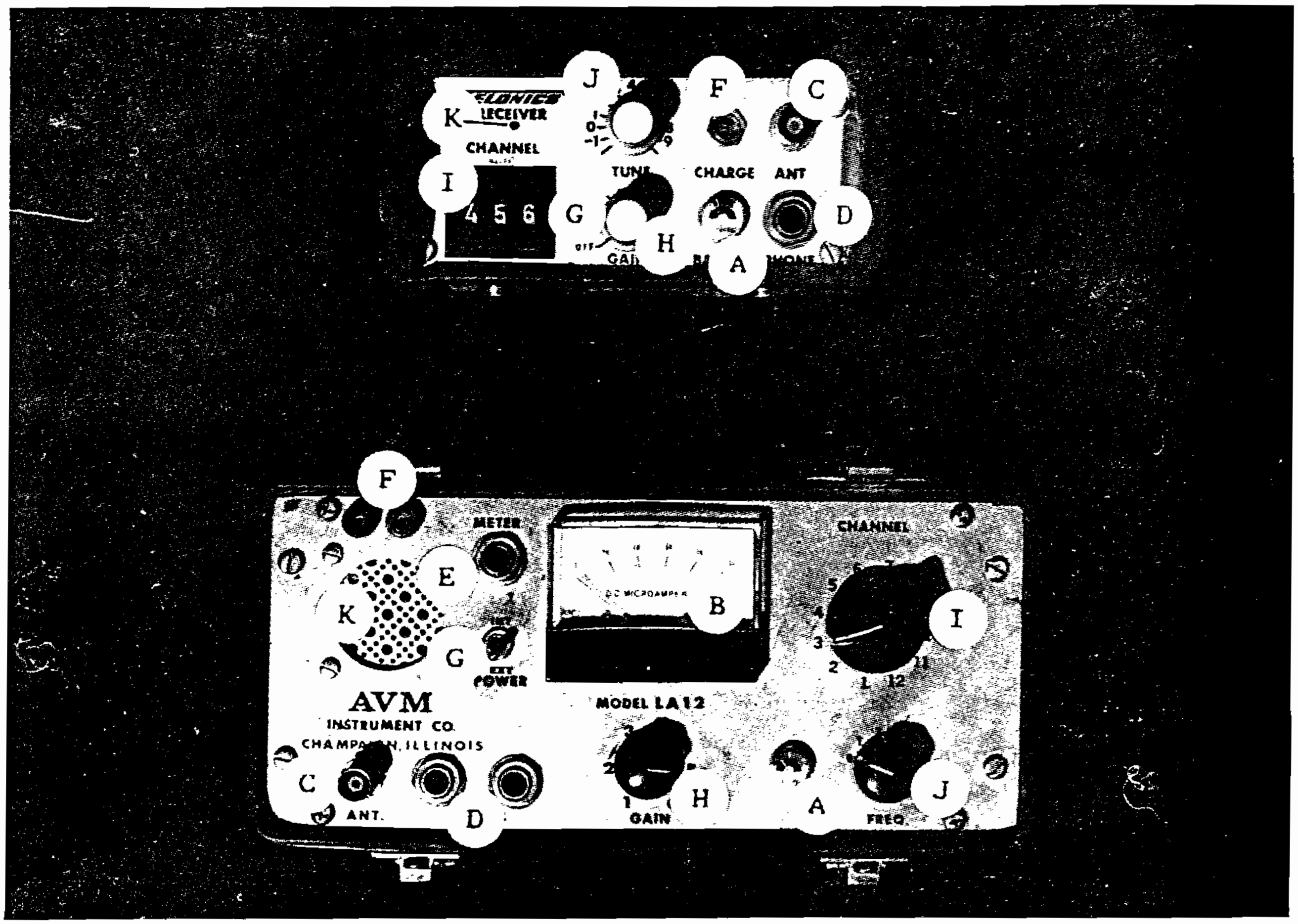


FIGURE 3. Control panels of two commercially available telemetry receivers with gauges: A – battery charge indicator, B – signal strength meter, connectors, C – antenna receptacle, D – headphone jack, E – external meter jack, F – external power source/recharge connector, controls, G – on/off switch, H – volume or gain control, I – channel selector switch, J – fine tune adjustment, and K – speaker

Let us take a moment to step through the process we would normally use in hooking up a receiver and tuning in a signal from a distant transmitter. For our purpose here, let us assume we are 'searching' for a transmitter on channel 3.

1. *Start by attaching the terminal on the end of the antenna lead (coaxial cable) to the antenna input receptacle on the receiver.* In doing so, do not place any sharp kinks or heavy strains on the coaxial cable where it exits from the terminal connector. Lock the connector down with an appropriate twist of the locking collar.
2. *Decide whether you wish to use the speaker in the receiver or a headset.* If you choose the latter, insert the plug (jack) on the end of the headset leads into the proper receptacle on the receiver panel. The primary advantage in using a headset is to reduce interference from the noises around you. When you start listening for very faint sounds, the noises associated with wind blowing in your ears, chirps of birds, insect songs and a multitude of other environmental noises become distracting and confusing. The large, soft ear cups on headsets can very effectively reduce interference from such sources.
3. *Turn on the power switch, activating the receiver.* If the gain (volume control) is separate from the power switch, make certain the gain control adjustment is at a very low level to avoid hurting or damaging your ears.
4. *Check the battery voltage* to ensure you have enough power to operate the receiver effectively.
5. *Gradually advance the gain control* until the 'hissing' of the receiver and/or background noise is audible, but not uncomfortable. Operating the receiver with the noise level too high (called over-driving the receiver) becomes obnoxious and uncomfortable and seldom improves your ability to discriminate weak signals.

6. *Select the frequency range* (channel) you wish to check; in our case channel 3.
7. *Rotate the fine-tune adjustment very slowly* while listening intently to the receiver output (presumably the antenna is in an elevated position). The pulsed signal from the transmitter will sound like a rhythmical beat or beep superimposed on the hissing noise of the receiver. *Move the fine-tune adjustment back and forth slowly until you hear a pitch or sound that is comfortable and easy for you to hear.* Most receivers use two or three step-down stages to convert the coming radio frequency to a much lower intermediate frequency. A beat frequency oscillator (BFO) is then used to convert the intermediate frequency to a frequency that is audible to human ears. This is done by comparing the intermediate frequency with a variable, but closely allied, frequency that is manipulated by the fine-tune adjustment. You hear the difference between the two frequencies. As a result, when the two frequencies are far apart, the difference is great and a very high pitch results. As you 'tune' the receiver, the two frequencies became closer, the difference is less and the pitch decreases. When you are tuned directly on the frequency of the transmitter, there is no difference in the two frequencies and no 'tone' is produced. As the BFO is adjusted beyond the frequency of the transmitter, the difference in the two frequencies becomes greater again and the pitch increases until it vanishes in the realm beyond the detection of human hearing (Figure 4). Some commercial receivers use an asymmetrical tuning process for the BFO which tends to blank out the signal on one side, resulting in the operator hearing the pitch change on only one side of the signal.
8. After having completed your task with that channel, repeat steps 6 and 7 with other channels of interest.
9. If you are trying to approach a transmitter, the volume of the receiver output will increase as you get closer. If the receiver reaches the limits of its ability to respond, you may appear to lose directional sensitivity of the antenna. This can be avoided by *slowly turning the gain control counterclockwise to decrease the amount of amplification* the receiver is providing. Inexperienced personnel have a tendency to operate receivers at higher gain levels than needed and may be less effective than they could be.
10. When you have completed your work, *turn the receiver power switch off, carefully disconnect earphones, antenna lead, etc.*, and store properly.

One point that deserves additional comment is that on most commercially available receivers the range of the fine-tune adjustment is greater than the separation of frequencies on the channel selector. As a result, if a transmitter is operating midway between two channels on the receiver, the same signal may be tuned on the high end of the fine-tune adjustment on one channel and on the low end of the fine-tune range on the next higher channel (see Figure 5). This can be misleading even to experienced personnel if not kept in mind.

Antennas

Antennas are an extension of the receiver and, as such, are connected directly to the receiver with a special type of lead called a coaxial cable. The function of the antenna is to pick up the alternations in polarity of the electromagnetic waves generated by the transmitter. The coaxial cable carries this 'information' to the receiver. To optimize this process, the antenna is 'tuned'

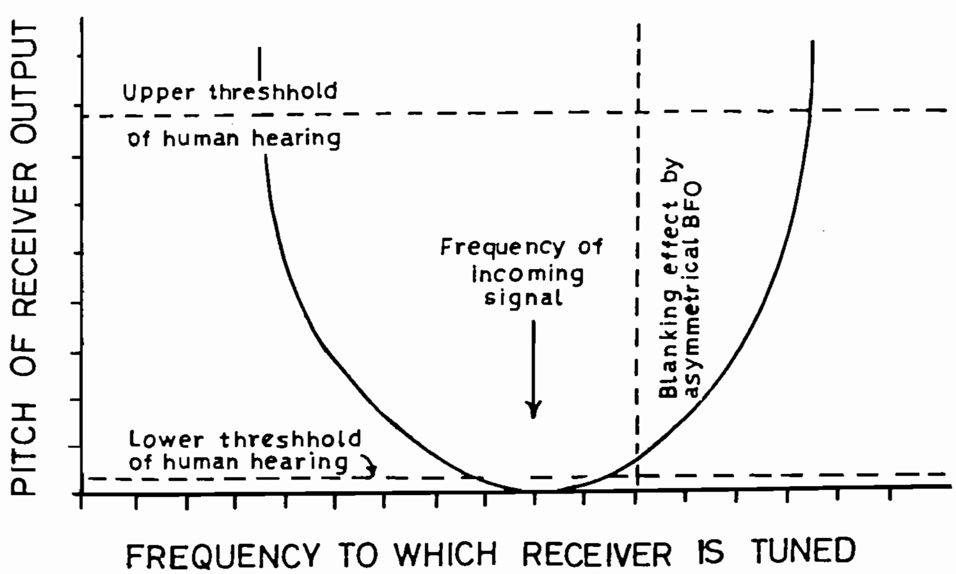


FIGURE 4. Diagrammatic explanation for the change in signal pitch of a receiver output signal associated with adjustment of the fine-tune knob (beat frequency oscillator)

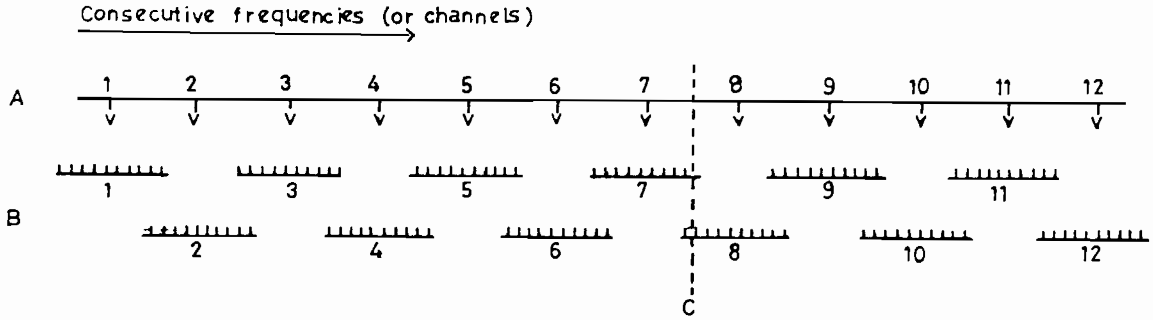


FIGURE 5. Diagram of the functional relationship between frequency (channel) selector and fine-tune adjustment in most commercial telemetry receivers: (A) frequency, or channel selector chooses *one* of a series of frequency ranges; (B) fine-tune adjustment shifts frequency tuning across a narrow range of frequencies in the immediate vicinity of the channel selected in A; (C) usually the fine-tuning range is greater than the separation between adjacent channels, sometimes causing confusion because a transmitter broadcasting midway between channels (e.g. channels 7 and 8) can be tuned in on the high end of the fine-tune range of one channel *and* on the low end of the fine-tune range of the next higher channel

to resonate efficiently at a relatively narrow range of frequencies (e.g. those tuned for 164 MHz may work over a range (162–6 Mhz). This tuning is achieved through a combination of the length and spacing of antenna elements, adjustment of a matching bar, and/or selection of the value of a tuning capacitor. Although most antennas seem relatively simple, they are sensitive pieces of equipment. They are probably mishandled and abused more than any other part of a telemetry system.

An antenna detects the changes in polarity of radio waves by comparing them with a reference or standard. Part of the antenna is sensitive to the incoming radio waves while the other part is the references, commonly referred to as 'ground'. This is achieved by connecting the ground side of the antenna to the frame of the receiver, antenna mast, or any other large metallic body by means of the braid, or shield, of the coaxial cable. Since we want the sensitivity to the signals to come *only* from the antenna, the 'hot' lead from the antenna is encased within the metallic braid (shield) of the coaxial cable. This isolates the hot lead from the influence of incoming radio waves along the length of the cable between the antenna and the receiver (see Figure 6). One of the more common antenna malfunctions results from separation of the braid, usually adjacent to the terminal connector, with a subsequent loss of a continuous ground between the antenna and the receiver. Gentle treatment, with a minimum of stresses, is always recommended when connecting, disconnecting or handling coaxial cables. The impedance rating of the coaxial cable should match that of the receiver. Most commercially available receivers are designed for 50 ohm input impedance.

Hand-held Antennas

These are so named because they are small enough to allow one person to use them as they are carried about. Four of the most commonly used types are depicted in Table 2. Each has advantages and disadvantages, and, depending on the circumstances, there are times and places where each might be the one of choice. Even using a metal paper clip as a tiny whip antenna may be preferred in some situations. Anything will work a little. We constantly need to ask whether some other antenna configuration might be more appropriate for the specific job we are involved with at the moment.

A whip antenna is not very useful for locating transmitters since it is a single straight piece of rod or spring steel that has been appropriately tuned and is equally sensitive in all directions. This type of antenna is useful in situations where transmitter location is not important but where maintaining radio contact for monitoring purposes, such as determining activity periods or physiologic functions, is the primary objective. This type of antenna would not need attention (e.g. rotation) as long as it is sensitive enough to cover the area in which the animal is apt to roam.

Loop antennas are extremely handy because of their small size and directional properties. These advantages

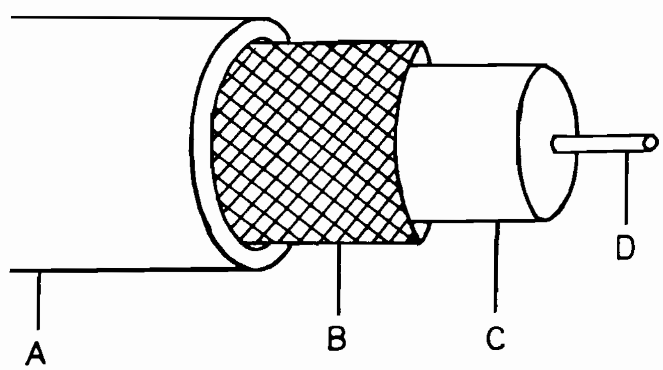


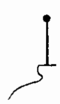
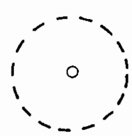
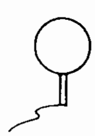
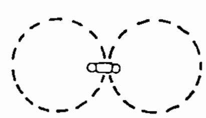
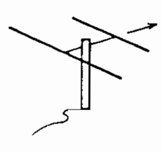
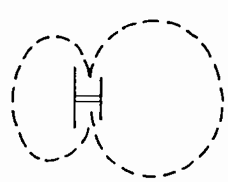
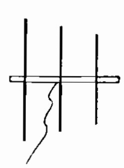
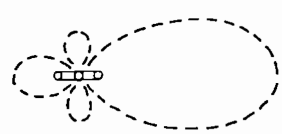
FIGURE 6. Cut-away drawing of a coaxial cable showing (A) protective rubber sheath, (B) metallic braid or shield, (C) foam or plastic dielectric, or insulation, and (D) centre conductor or 'hot' lead

are offset by the fact that they are seldom as sensitive as some other types of antennas and the pattern of sensitivity is ambiguous. The plane of the transmitter can be established, but from one location you cannot tell whether the signal is coming from the front or from behind. Incidently, either the peak or the null (the antenna facets from which no signal is received) can be used to indicate the direction from which the signal is coming. The fastest and surest way to resolve the directional ambiguity is to move perpendicular to the plane established at the first location, and, establish a second plane by determining the direction from a second location. By mentally extrapolating the intersection of the two planes, you know in which direction to proceed to approach the source of the signal and you have some idea how far you might have to go to reach it.

Yagi antennas are perhaps the most commonly used hand-held antennas. Since the *'H' antenna* is the first step in development of a yagi we will discuss them together. We previously mentioned that a whip antenna is omnidirectional, essentially having equal sensitivity in all directions. If we place another metal rod, or element, in close proximity to such a whip, we influence the electromagnetic waves and start to shape the pattern of sensitivity, making the antenna more sensitive on the side opposite to the added element. Such an element added behind the driven element is called a reflector. This essentially is the configuration of an 'H' antenna. Needless to say, length and spacing of the extra element are important. The increased sensitivity, or gain, of such an antenna generally makes it more desirable as a direction-finding instrument. Also, the lack of ambiguity lets you direct your attention immediately to approaching the source of the signal.

If the addition of one element increases the sensitivity in one direction, what about adding more than one extra element? This is essentially what is done in making yagi antennas. Any number of additional elements can be added (in a straight line); the more elements that are added, the more the pattern of sensitivity is shaped. One point to remember is that after the addition of one reflector, all other elements are added in front of the driven element (even if they number 10 or more). Elements placed in front of the driven element of a yagi antenna are called directors (Figure 7). Every time you double the number of elements on an antenna, the sensitivity is increased about 3 db (decibels) in the forward direction. This increased sensitivity towards the front comes at the expense of sensitivity to the sides and back. We need to remember there are side lobes and a back lobe in the sensitivity pattern of a yagi antenna, but they are much smaller than the forward lobe. This becomes quite important in fixed-station direction-finding work because you may

TABLE 2. Comparison of characteristics of several types of hand-held antennas

Antenna Type	Physical Configuration	Pattern of sensitivity (vertical view)	Comments
WHIP			Omnidirectional. Convenient for monitoring where location is not important. If used for locating transmitters, must depend on relative signal strength to indicate relative proximity.
LOOP			Signal pattern is ambiguous (two nulls and two peaks) which the operator must resolve. Very convenient to use in confined situations or dense brush (e.g. bamboo thicket) but may be less sensitive than other types.
'H'			Pattern is not totally ambiguous but generally does not provide a strong narrow peak in the pattern. Relatively convenient to carry and use.
YAGI (3-element)			Pattern is not ambiguous as long as back lobes and side lobes are not confusing. Provides a strong, sensitive and relatively narrow peak sensitivity. More sensitivity in forward direction than other types. Probably the antenna of choice in open or semi-open terrain and frequencies above 140 MHz.

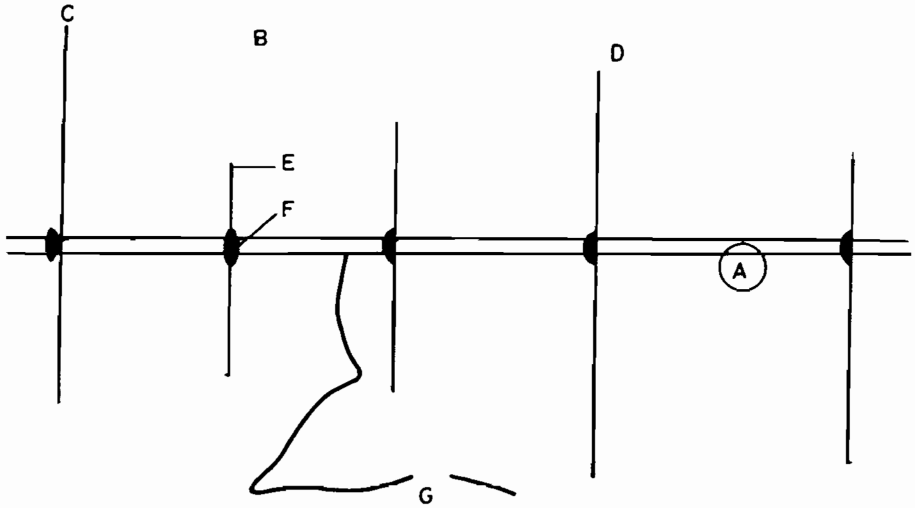


FIGURE 7. Five-element yagi antenna with parts labelled as follows: (A) beam; (B) driven element; (C) reflector; (D) directors; (E) gamma matching bar with slide adjustment; (F) tuning capacitor; (G) coaxial cable with BNC connector

not know in what direction the antenna is pointed and there is no automatic correction should an error occur. Most yagi antennas used as hand-held devices have three or four elements. Additional elements become cumbersome and difficult to handle in the field. Yagis can be quite unmanageable when working in brush or dense forest situations because the antenna is relatively large and the elements frequently get caught on twigs and limbs. Normally there is a preference to use yagi antennas with the elements directed vertically because theoretically there is less attenuation (weakening) of the vertically polarized portion of the signal. I have seen occasions, however, when placing the elements horizontally worked better. Experimenting may be the best way to resolve the situation.

When trying to locate transmitters in the field with hand-held antennas, I recommend the following procedures:

1. *Seek a hilltop or other topographical prominence* in the vicinity where you expect the transmitter to be. This may be in the vicinity where you have located the animal previously or where, for other reasons, you suspect it might be. To the extent practical, try to stay in the open, as opposed to heavily forested hills, to minimize problems with signal 'bounce' or penetration through foliage.
2. *Follow steps 1–6 under receiver operation* (pp. 87–88).
3. *Holding antenna aloft in one position, slowly rotate the fine-tune adjustment* through the range of frequencies. If a signal is heard, immediately try to obtain the clearest signal possible through adjustment of the fine-tune knob without moving the antenna. Make a mental note of the fine-tune setting in case you lose the signal. Skip to step 6 (below).
4. *If no signal is detected, rotate your body about 45 degrees so that the antenna is pointed in a new direction* and repeat step 3. Continue this process until a signal is detected or you have covered the terrain commanded from that location.
5. *If no signal is detected from that point, you can wait 15–30 minutes and try again*, hoping the animal has become active or moved within receiving range, *or* you can seek another nearby topographically desirable location from which to search and repeat steps 2 and 3. If a signal is detected, continue with step 6.
6. *Slowly rotate your body to swing the antenna through a complete circle.* Note the positions of maximum and minimum signal strength from which you can deduce the direction or plane (depending on antenna type) in which the signal is originating. The reason for rotating your body rather than swinging the antenna is because with any hand-held antenna *you* are part of the antenna and your body is influencing the antenna pattern. Consequently, you should try to maintain your relationship with the rest of the antenna as constant as is practical.
7. Through experience you will develop an ability to estimate how far away the transmitter is based on the strength of the signal received. You obviously will have to take into consideration the relative strength of the transmitter you are using, the amount of gain your receiver is providing (gain control setting plus battery voltage), the degree of topographic prominence, particularly elevation, associated with your monitoring location, physiographic features of the area where the transmitter might be (e.g. level plain, ridges and draws, hillside facing you, etc.), and perhaps other criteria.
8. *Decide whether you want to approach the transmitter directly or obtain more information first.* Your decision

may be influenced by how far away you think the transmitter is, whether you think you can get closer more easily by some other route, and whether you wish to approach the transmitter without being detected by the animal to which it is attached (e.g. if you wish to locate it to make behavioural observations).

9. *If you choose an indirect route, identify some other prominent topographic feature from which you can gain additional information* by repeating the process identified above. It is particularly helpful if you can find a location not in a direct line with the transmitter and the initial point from which you identified the signal.
10. *If you choose the direct approach, gradually reduce the volume of the receiver output as you approach the transmitter.* This will let you use the most sensitive part of the antenna pattern and more closely identify the direction of the signal. Keep in mind that frequently as you descend from hilltop, you may move out of line-of-sight reception resulting in diminution of the signal (sometimes you may even lose contact with the transmitter). This does not mean you are going in the wrong direction but rather that you are moving into a less favourable receiving situation. This is particularly common if you are working with a faint signal.
11. As you get very close to a transmitter, your regular antenna may become too sensitive and the signal may overload the receiver even at the lowest gain settings. Under these conditions you may lose all sense of directionality with your antenna. One solution is to switch to a less sensitive antenna for more precise location of a transmitter that is not readily evident. One technique that I have employed, particularly when the transmitter is buried, is to unhook the regular antenna and insert a short piece of wire (e.g. a straightened metallic paper clip) into the 'hot' lead portion of the antenna receptacle on the receiver. This creates a poorly tuned whip. By holding the receiver at arm's length and using my body as a reflector, I essentially create a directional antenna suitable for very close work. Another option which has been useful in very brushy or submerged habitats is to strip 1 to 2 inches of braid from the end of a piece of coaxial cable (which has an appropriate terminal on the other end to plug into the antenna receptacle of the receiver), and then tape the coaxial cable along some kind of non-conducting stick. Again you have a relatively insensitive whip antenna which you can use as a probe to pass into and around bushes or even under water. By using relative signal strength, you can discern whether you are moving the probe towards or away from the transmitter and hence eventually locate the transmitter.

We will leave our discussion of hand-held antennas at this point except to urge that one must keep an open mind whenever using hand-held antennas and constantly be aware of the variety of explanations that could account for the electronic events one experiences.

Fixed-station Antennas

When it is desirable to intensively study the ways animals use space, or constant surveillance is desired, there are tremendous advantages in using fixed station telemetry techniques. In general, these techniques use more sophisticated antenna technology to simultaneously determine the azimuth, or bearing, to a transmitter from two or more locations. Knowing the precise location of each receiving antenna and the direction (bearing) from which the radio signal was received at each antenna, it is possible to calculate and plot the location of the transmitter using trigonometric functions. The advantage of such techniques is that frequent relocations of one to many animals can be made without risk of disturbing the animals. The bigger antenna systems provide greater sensitivity and greater precision in estimating the direction from which the radio signal originates.

Fixed-stations are typically located on prominent hills or ridges and consist of larger rotatable yagi antennas perched atop a tower or pole. The normal configuration is to use two yagis side-by-side (this is called horizontal stacking) and coupled together (Figure 8). There are several ways of coupling the antennas but the most dependable is to use a device called a 'hybrid junction' or 'hybrid tee'. The antennas can be coupled in-phase, so that the signals arriving at each antenna reinforce each other and the two antennas work together to provide a stronger signal. In this mode the pattern of sensitivity is similar to that of a single yagi (Table 3) except that the pattern is shaped more and, because there are twice as many elements, the antenna provides 3 db more gain.

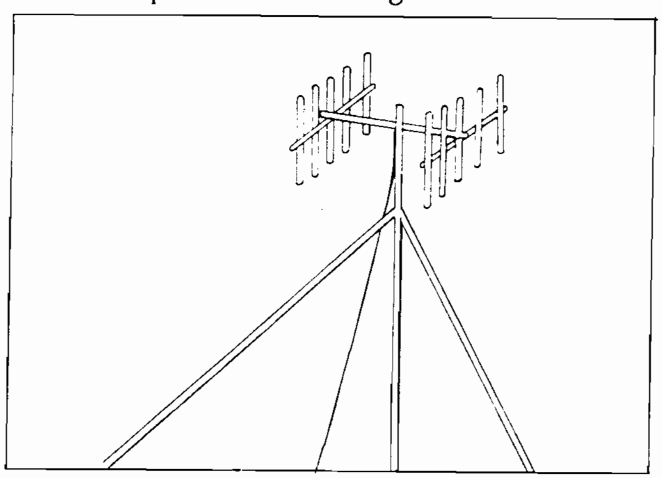
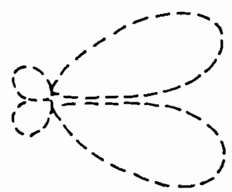


FIGURE 8. Two five-element yagi antennas stacked horizontally for fixed-station telemetry

TABLE 3. Comparison of characteristics of horizontally stacked yagi antennas coupled in-phase and out-of-phase

Coupling mode	Pattern of sensitivity	Remarks
In-phase (sum mode)		Two antennas work together to provide a single large front lobe with 3 db more gain. There is relatively little improvement in the directivity.
Out-of-phase (difference mode)		The signal produced is related to the difference in the phase of the signal sensed by the two antennas. If the signal arrives simultaneously, there is no difference in the signals and a null (no signal) is produced. This occurs when the source is equidistant to the two antennas (e.g. directly ahead or behind). There are two large front lobes and two or more back lobes. Sensitivity between the two front lobes falls off very sharply permitting a very precise estimate of the bearing.

On the other hand, the antennas can be coupled out-of-phase, in which case the strength of the signal to the receiver represents the difference between what is sensed by the two antennas. A signal that originates equidistant from each antenna will be sensed equally and, since there is no difference, no signal is sent to the receiver. However, as the source moves away from being equidistant, the signals arrive at the two antennas at slightly different times which effectively shifts the signals received by the two antennas out-of-phase and the difference between the signals detected by the two antennas is transferred along the coaxial in the form of an electrical current. If the signal is far enough towards one side, the radio waves arriving simultaneously at the two antennas are completely out-of-phase (opposite polarity, see Figure 1) resulting in a big difference between what the two antennas sense, and a maximum signal is detected by the receiver (Table 3). The sharp null (lack of signal) between the two major lobes of the pattern can be measured quite accurately. Antennas coupled in this manner create one of the more powerful tools for studying movement patterns of wild animals.

Collection of high quality data depends on maintaining accuracy and precision in estimating the location of the transmitter. This means reducing the effects of systematic *and* random errors in the triangulation process as much as possible. Careful attention to the following can help: (1) location of monitoring stations (antenna towers) in relation to the area under surveillance; (2) proper selection and mounting of antennas as well as maintaining the proper orientation of them; (3) use of the most appropriate azimuth read-out mechanism; and (4) maintaining synchrony in readings from two or more locations.

I have already alluded to the desirability of locating fixed-station antennas on prominent hills or ridges overlooking the areas of interest. Disregarding the reality that such topographic features are seldom distributed as we would like, there are two ideas we should keep in mind when selecting locations for fixed-station telemetry work. One is related to the average distance the tracking stations are from the instrumented animals and the other relates to the position of the stations relative to the animals. Both affect the accuracy and precision with which the locations of the transmitter-equipped animals can be determined. In the first instance, an error of one degree in azimuth from a tower equates to a lateral displacement of 15 metres at a distance of one kilometre; at a distance of 5 kilometres the same error would result in a lateral displacement of about 75 metres. The farther away a tower is, the greater the displacement associated with each degree of error. If you expect your study animals to utilize a large area, you will want the towers farther away than if you only expect them to use a small area. At the same time you have to recognize that there will be increasing loss of precision as the stations are set progressively farther apart. If you set the stations too far from animals that use only a very small area, you may not be able to detect any movement at all. The second aspect with regard to precision results from differences in the amount of error associated with the position of the transmitter relative to the stations. The estimated location of the instrumented animal is derived from extending the azimuths obtained from each tower until they intersect. The most precise estimates are those in which the two azimuths are perpendicular at the point of intersection. These points correspond to the circumference of a circle whose diameter is the baseline between the two towers (Figure 9). At the same time, errors associated with

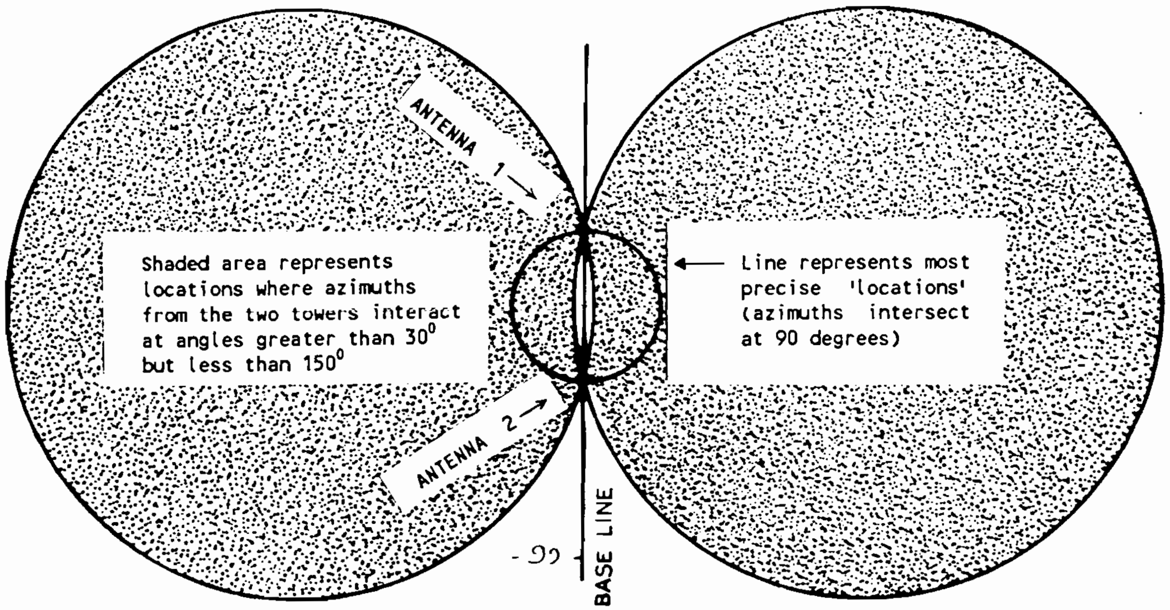


FIGURE 9. Areas of good (shaded) and poor (clear) precision associated with triangulation from two locations

azimuths intersecting at angles less than 20 degrees or greater than 160 degrees become so large that the estimates become unreliable and meaningless. The practical application of this is to recognize that there is an area adjacent to the baseline (a line extended through the two towers) which will provide very poor data, at best. Hence, given the choice, it is best to keep the baseline somewhat removed from the primary area the study animals may be using.

In selecting yagi antennas to be used as a pair, select ones with as closely matched electrical properties (sensitivity) as possible. This should be determined by someone who is knowledgeable in antenna tuning procedures. Since the relative phase of the wave of incoming signals sensed by each antenna and transferred to the hybrid junction is critical (and distance equates with shifts in phase), it is essential that coaxial cables connecting each antenna to the hybrid junction are the same length. The two antennas should be mounted parallel and spaced 3/4 of a wavelength apart (actual dimensions will depend on the frequency involved). It is also preferable for the antenna array (the entire device at the top of the mast) to be balanced both physically and with regard to wind-loading to ease problems in tuning the mast and holding it steady.

A precise mechanism to determine the direction in which the antenna is pointed is essential. This usually involves some sort of compass rose (a circular ring with 360 degree markings on it) and a pointer. I prefer to have the rose attached to the antenna mast, so that it rotates with mast, and to keep the pointer stationary. This allows the operator to keep his eyes in the same relative position to the pointer and the rose, thus avoiding parallax problems caused by the rose and pointer not being in the same plane (Figure 10).

Without correctly establishing and maintaining the orientation of the antenna system, the data collected may be of little value. Many people erroneously assume that the electrical pattern of an antenna, or

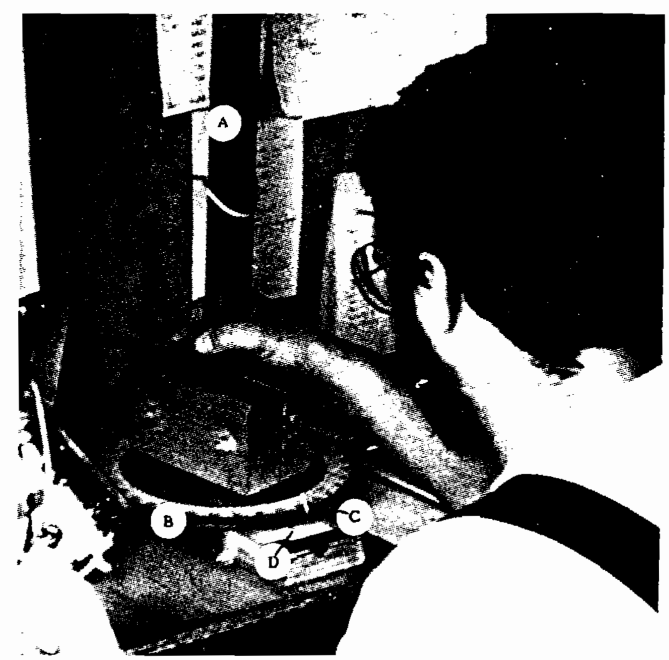


FIGURE 10. Azimuth read-out mechanism with the following parts identified: (A) antenna mast; (B) compass rose attached to mast; (C) stationary pointer; and (D) alignment mark to ensure a common sighting plane for all readings

antenna system, is aligned with the physical structure. On the contrary, it is not unusual for the electrical pattern to be skewed several degrees to the left or right of the physical pattern of the antenna. The best procedure for maintaining antenna orientation is to use a beacon transmitter as an electronic reference from which bearings are measured. The precise location of each antenna tower, as well as the location of the reference transmitter, should be established with a surveyor's transit (do not forget to also survey some known or measured distance to establish a scale for the map to be developed). This will provide a known azimuth (compass bearing) from each antenna tower to the reference transmitter. The position of the rose at each tower can be adjusted when the reference signal is centred in the null of the antenna pattern with the correct azimuth indicated. Thereafter, azimuths to the animal-mounted transmitters can be read directly. An alternative procedure does not require adjusting each rose but includes reading the azimuth to the reference transmitter just like all the other transmitters of interest. Subsequently all azimuths need to be recalculated based on a knowledge of the correct azimuth to the reference transmitter and the difference between azimuths to the reference and the animal-mounted transmitters. Such computations can become laborious and subject to error unless computer facilities are available. Even if the compass rose is adjusted to read correctly, the bearing to the reference transmitter should be checked at least once every hour of use to ensure that the system is properly aligned.

The final source of error that I wish to mention involves failure to obtain azimuths from each station at the same time. If an animal with a transmitter moves between the time the two azimuths are taken, appreciable errors can result, especially if the animal is relatively close to one of the stations. There are several means of maintaining synchrony in taking readings. The most convenient is to have two-way radio communication between the two stations. Perhaps the simplest technique, however, is for the operators of the two stations to agree upon a timed sequence for making readings and upon a schedule to be maintained throughout the monitoring period. This amounts to planning ahead *and* adhering to the plan.

After (1) the receiving stations have been properly situated, (2) antennas are properly matched, mounted, coupled out-of-phase, and oriented with regard to a reference transmitter, (3) an accurate and trouble-free read-out mechanism is employed, and (4) a schedule has been agreed upon to synchronize data taking, it is essential to use a standard procedure for making readings. The process I recommend follows:

1. *Connect the coaxial cable coming from the hybrid junction to the antenna receptacle on the receiver.*
2. *Orient the antenna so that the front of it is pointed in the general direction of the reference transmitter.* It is best not to point it directly at the reference transmitter because that would place it in the null portion of the pattern.
3. *Tune the receiver to the frequency of the beacon transmitter.*
4. *Reduce the receiver gain until the signal is of soft to moderate amplitude.*
5. *Rotate the antenna 360 degrees to make certain you are working with the null between the two main lobes of the antenna pattern.* Be aware that you may be wrapping the coaxial cable around the antenna mast.
6. *Very slowly rotate the antenna from one of the main lobes towards the frontal null.* Note the exact reading (azimuth) where you can no longer detect the signal. *Record that reading.*
7. *Without changing any settings on the radio receiver, rotate the antenna until the signal can be heard on the opposite side of the null.*
8. *Very slowly rotate the antenna in the opposite direction (back towards the null)* and again note the exact reading where you no longer detect the signal. *Record that reading also.* That completes the readings on the reference transmitter for that time. Always move from a good signal towards the null and read each side of the null. *Do not* use the point where you reacquire the signal because your mind functions differently between losing and recognizing sounds. Ultimately you will calculate the average (mean) of the two readings, one from each side of the null, and use that as the azimuth to the transmitter. A sample recording sheet is presented in Figure 11.
9. *Search for other transmitters of interest using techniques outlined in steps 2–4 under hand-held antennas. When a signal is detected, repeat steps 5–8 above to determine the azimuth to that transmitter.*
10. CAUTION: *Do not leave your radio receiver connected to the coaxial cable coming from the antenna during an electrical storm.* A direct hit from a lightning bolt on the antenna could destroy your receiver, or it could be disabled by exposure to intense electrical fields even though an electrical discharge did not occur. *For your own safety, move off the top of the hill to a safer location.*

Ultimately you will have to plot each of the estimated relocations on an appropriate map. This can be accomplished manually through the use of protractors or drafting machines, or it can be accomplished with appropriate programming if you have access to a computer. The real rewards of careful planning and data collection become evident as relocations are plotted (Figure 12).

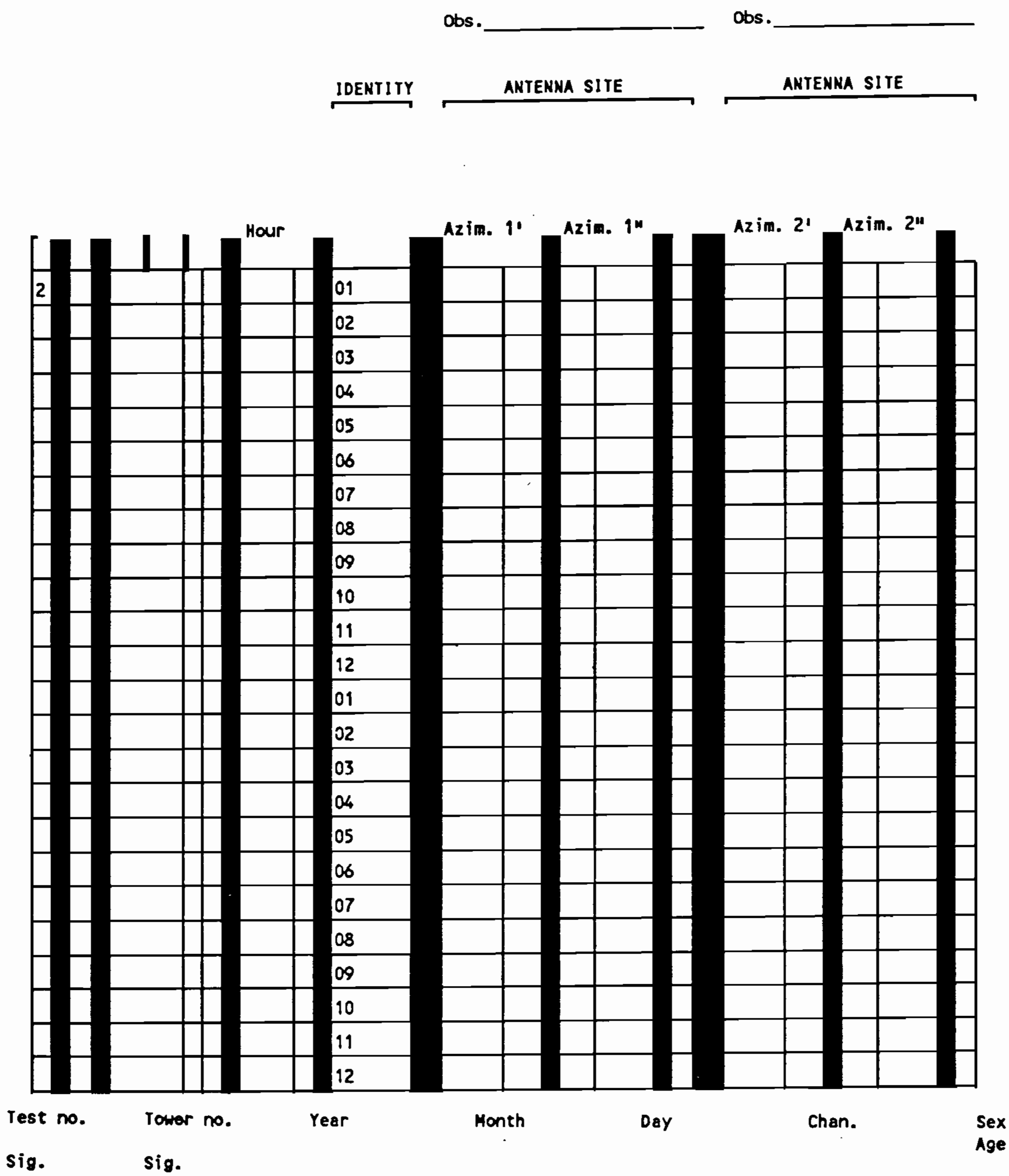


FIGURE 11. Sample form for recording data from fixed stations

Aircraft Antenna Systems

Occasionally radio-instrumented animals may move out of range of conventional ground-based receiving systems, and it is desirable to rapidly search an extensive area to locate the missing animal. In other instances, (e.g. to check migratory routes) studies may only require sporadic checks of animals over rather extensive areas. In such cases, mounting receiving equipment on aircraft may be an expedient means of accomplishing the objectives because aircraft usually (1) provide a higher platform from which to search, with an attendant improved receiving capability, and (2) can rapidly cover extensive distances which might otherwise require hours or even days to cover with ground-based systems.

The manner in which the equipment is oriented and attached to the aircraft can substantially affect the effectiveness and efficiency with which transmitters can be detected and located. Theoretical considerations sug-

Adult female
coyote

From
September 19, 1979
1610 hours

To
September 20, 1979
0750 hours

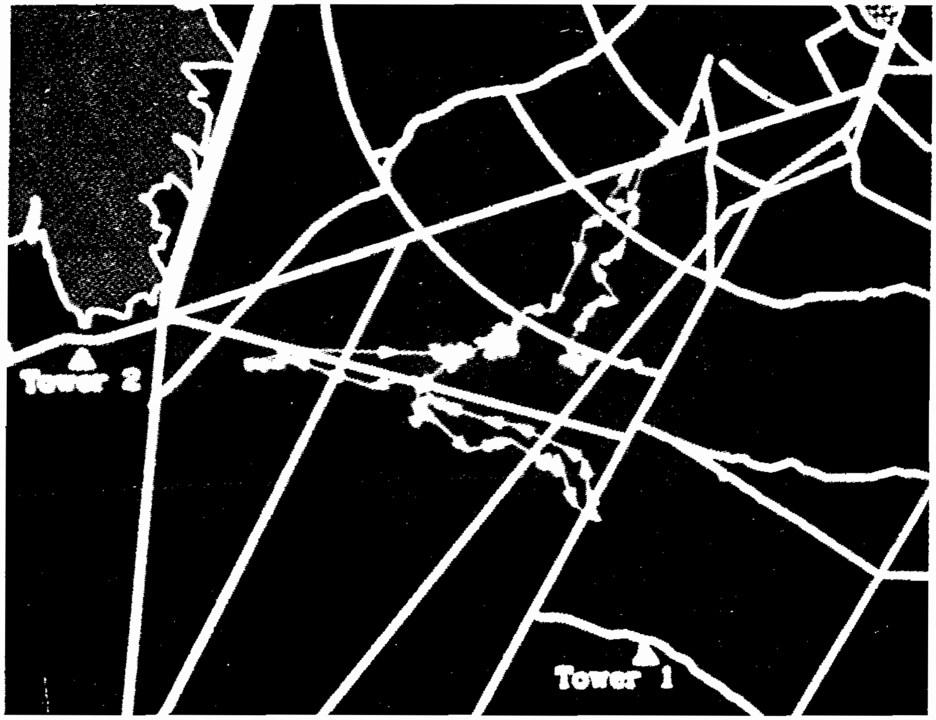


FIGURE 12. Example of coyote (*Canis latrans*) movements determined via fixed-station telemetry. Arrows represent successive animal locations at 10 to 15 minute intervals

gest that the primary concern should be to direct the most sensitive portion of the antenna pattern lateral to the flight of the aircraft so that as broad an area as possible can be covered as you fly along. Normally it is not essential to have a strong antenna pattern in the direction the plane is going because you will eventually be there.

The most commonly used procedure is to attach a yagi antenna to each strut on a high-winged aircraft. The antennas are directed perpendicular to the fuselage with the front of the beam angled slightly toward the ground. Frequently the intake tubes for the cabin air supply provide convenient passage for bringing the antenna leads into the cabin. This avoids draping the leads through open windows or crushing the coaxial cable in the door gasket of the plane. Inside the cabin, the leads from each antenna should be coupled to a coaxial switch, with the common output from the switch being coupled to the antenna receptacle on the receiver. *Be certain you know which antenna is coupled to each of the positions of the coaxial switch.* The coaxial switch allows you to alternately 'listen' with one antenna and then the other. It is *not* recommended that the cables be connected so that both antennas are used simultaneously because sensitivity is reduced by half or more (a signal picked up by one antenna would be split with part of the power going to the receiver and part of it retransmitting from the opposite antenna).

In use, the recommended procedures for aerial search and location are:

1. *Beforehand, identify the area to be searched and the search pattern to be used.* Convey this information to the pilot and to appropriate civil authorities.
2. Attach the equipment to the plane and couple it together.
3. *Fly the search pattern at the desired altitude,* usually 1000 to 1500 feet above the terrain.
4. *With coaxial switch in one position and the channel selector switch on the desired frequency, rotate the fine-tune adjustment on the receiver* slowly through a reasonable range to ensure that you detect any incoming signal.
5. *Switch the coaxial switch to the other antenna and repeat step 4.* Continue doing this with all frequencies of interest as you fly along.
6. *When you detect a signal, carefully adjust the fine-tune control until a pleasant tone* is heard and adjust the gain control to an appropriate level.
7. *Without changing receiver settings, switch back and forth between the two antennas.* Tell the pilot to turn the aircraft in the direction of the antenna providing the loudest signal. The signal from that antenna should gradually diminish and the signal from the other antenna should increase. Continue doing this until the two signals are equal. The aircraft should be headed directly toward the transmitter. As you fly

toward the transmitter, the signal should get progressively stronger. If you are moving away from it, the signal will gradually become weaker and disappear. Two cautionary notes: (1) do not compare signal strength from the two antennas while the airplane is in a banking turn; and (2) if you are working with a weak signal, you may lose the signal altogether because a less sensitive portion of the antenna pattern is pointed at the transmitter. If this happens, keep flying in the same direction and listening alternately to each antenna. Eventually you will reacquire the signal.

8. *Reduce the gain level as the plane approaches the transmitter.* When the plane passes directly over the transmitter, the signal will overload the receiver even at the lowest gain settings and you should hear a very loud clapping sound instead of a beep.
9. *If a more precise location is desired,* have the pilot reduce altitude to 200–500 feet above terrain and approach the transmitter a second time, preferably from a different direction.
10. *Resume search pattern for other transmitters of interest.* Aerial searching can be a very effective and efficient means of locating transmitters spread over extensive areas or ones that have moved beyond the capabilities of normal ground-based receiving equipment. Several cautionary comments are relevant: (1) attach all equipment securely to the aircraft without risk of damaging the plane; (2) the pilot has authority over what will or will not be done while the aircraft is in the air; (3) wind-drag from antenna can appreciably reduce air-speed and change flight characteristics of aircraft; (4) do not attempt aerial telemetry activities when flying conditions are marginal; and (5) proper planning can increase efficiency and minimize costs of aircraft rental.

Transmitters

The application of radio technology to the study of wild animals was impractical prior to the development of transistors and diodes. They permitted fabrication of simple, small, and light-weight circuitry capable of radiating radio signals and suitable to be attached to animals.

Radio Beacons

Any circuit that produces a radio signal can serve as beacon, or target, suitable for location through use of directional antennas. In their simplest form (e.g. a Col-Pitts oscillator) such beacons may consist of only 7 or 8 electronic components. Even today, when ultra-small, light-weight transmitters are required, as might be the case for small birds or rodents, these very simple circuits are used.

While these simple circuits were the basis for the original radio beacons which gave birth to radio tracking of wildlife, they were unstable and resulted in variable performance, as evidenced by transmitters that shifted radio frequency, pulse rate, and/or radiated power with changes in temperature, tuning adjustments, voltage, and other factors. This created a number of operational uncertainties, including: (1) not knowing where to tune a receiver to pick up the signal; (2) maintaining proper identification when several transmitters with only slightly different frequencies are used; (3) varying reception ranges; and (4) unpredictable operating life of the transmitter. The development of more complex circuits, which was greatly enhanced when integrated circuit chips became available, significantly improved operational stability of transmitters and created units with more predictable operating characteristics.

When selecting or designing transmitter beacons for studies involving intensive direction-finding, it is generally better to keep transmitter pulse rate above 60 per minute, and preferably around 100 per minute. The direction, or bearing, to the signal source is inferred from relative signal strength when the receiving antenna is pointed in several different directions. Most people can more readily discern relative differences in amplitudes of sounds if they are less than one second apart. Discriminating amplitude differences at longer intervals becomes increasingly difficult.

Transmitters for Sensing Position, Motion, and Mortality

The simultaneous miniaturization and increased sophistication of electronic circuits in recent years has resulted in transmitters which not only generate signals which can be identified and traced from a distance but also provide opportunities to gather additional information from the animal or its surroundings. Mercury tip-switches and piezoelectric elements have been added to transmitters as motion detectors. Depending on how they are incorporated into the circuits, they can change transmitter pulse rates to indicate changes in position of the animal (sitting up or lying down, head up or head down, etc.), changes in momentum, or provide an 'alarm' if the transmitter does not change position within a specified period of time (i.e. signal potential death of the instrumental animal). In many instances the activity periods of instrumented animals can be inferred simply from variations in strength of quality of the radio signal associated with differing radiation patterns or tuning characteristics as the animal moves or turns the transmitting antenna. Activity or movement can also be indicated more definitively by letting the motion transducer (tip-switch or piezoelectric element) trigger extraneous transmissions which are superimposed upon the base pulse rate of the transmitter.

Transmitters for Physiologic Monitoring

Transmitting information about body functions of free-ranging animals is one of the more complex applications of radio telemetry. Increased sophistication is needed in both transmitting and receiving portions of the telemetry system. A transducer, or sensor, is needed to detect appropriate body changes that signify the events of interest (e.g. heart rate, body temperature, etc.) and convert that 'information' into changes in the transmitted signal. Such sensors usually detect changes in electrical potential, resistance, or capacitance created by some part of the body. This is then used to either modify the pulse rate of the transmitted signal or is coded on the radio frequency carrier by modulating the transmission. In either instance, the receiving equipment must be capable of detecting and/or decoding the changes in the signal to 'recover' the information.

Special problems are encountered in this type of telemetry. Since deep body functions are usually involved, the transducer, or sensor, must be at an appropriate location. Running wires (frequently called leads) from the sensor to the transmitter is one option but is generally not very satisfactory if the transmitter is external to the animal's body. Some of the risks include damage to the leads, possible entanglement of the leads, or having the animal tear out or disturb the sensor. The other option is to implant the transmitter either under the skin or in the body cavity. In such situations, additional problems need to be solved. One is the necessity to package the electronic circuitry, including the antenna, so that it will not injure or hamper the animal but at the same time protect the electronics from the very corrosive body fluids in which they are immersed.This is a very specialized area and the wildlife biologist is well-advised to leave these problems to experts and to purchase equipment from companies that specialize in these types of applications. The second problem associated with implanted transmitters is the very short transmission range normally encountered because of signal attenuation within the body. While some studies can acquire information directly from implanted transmitters, in most instances it is necessary to transmit the information via a two-stage process. The implanted transmitter radiates a weak signal from within the body which is detected by an external electronic package which includes both a radio receiver and transmitter. The external package relays the signal, along with the coded information, usually with more power and an antenna better suited for broadcasting over long distances.

The greatly increased electronic requirements of such transmitters and receivers, as well as the typical involvement of a 'repeater' 'transmitter which must have both receiving and transmitting circuits, substantially increases the cost of equipment. Before purchasing such equipment, the biologist should carefully consider whether the information desired is really needed.

Selecting a Transmitter

Design of a transmitter to be carried by an animal is one of the most critical aspects when preparing for a study involving radiotelemetry. Telemetry offers an opportunity to gather information that would otherwise be impractical to acquire but is offset by the risk of causing aberrant behaviour or activities by the animal as a result of carrying the required instrumentation. Consequently, the desired electronic performance must be balanced against the possible inconvenience it may cause the animal. At the same time, the cost of fabricating or purchasing transmitters frequently places severe constraints upon what is practical. There are no set procedures for achieving such compromises because each study has its own objectives, constraints, and possibilities. My own approach includes the simultaneous consideration of three questions.

What information is essential? This includes type of data, number of subjects, frequency and/or durations of data acquisition, etc. Will a simple beacon suffice, or does additional information need to be conveyed from the animal?

What kind and size of package can the animal reasonably be expected to carry? This includes not only the weight and dimensions of the package but also the manner in which the package is to be carried. The degree of inconvenience to the animal must be a primary concern.

What electronic performance is essential and what might be desirable? How important is frequency stability and what are the requirements for reception range, transmitter reliability, and *longevity* of the transmitter?

It seems obvious that smaller and lighter electronic packages will be less disruptive to the animal. How the package is situated on the animal also grossly influences the amount of discomfort associated with carrying the transmitter. Relatively few studies have been made to determine the effects transmitters have on the animals that carry them. In most cases where this has been studied, animals with transmitters tend to spend more time in comfort movements like grooming and preening. They tend to spend more time feeding and may be less attentive to danger. It is not unusual to find relatively high mortality rates of instrumented animals, with a substantial portion of it due to predation. Additional studies of the effect transmitters have upon animal behaviour and survival are needed to better understand the influence they have on the very things they are designed to help study.

Biologists must also be concerned with the factors that influence the longevity and reliability of transmitters in the field. Some of the major factors are summarized in Table 1. The seemingly high cost of many commercially available transmitters is not to send biologists seeking more economical means of acquiring equipment. Generally the price of the transmitter is small in relation to the total investment involved, when the costs of personnel, travel, and capturing and handling animals, are included. Premature failure of transmitters will, at the least, increase experimental error and can negate the total study investment if an appropriate end-point is not reached. The best way to minimize such losses is to do as much as practical to ensure quality in the transmitters from the outset.

Telemetry Tomorrow

Innovations in electronics as well as techniques for applying them are constantly increasing the scope and potential for studying wild animals via telemetry. Miniaturization of electronic circuitry has significantly reduced the size and weight of radio transmitters. Solar cells are sometimes incorporated to produce power to run transmitters or recharge batteries, allowing additional reduction in the weight of transmitter packages. Radio tracking movements of polar bears and sea turtles from earth satellites has already been done. The current merging of telemetry and computer technologies is particularly exciting because it permits fast, sophisticated statistical analysis of the data on animal movements and physiologic functions. Computer analysis of sequential locations taken simultaneously on a series of animals can create movies depicting animals' movements with regard to each other, permitting new insights to animal behaviour. Additional possibilities can be expected as a new generation of receivers, possibly in the form of correlation receivers, significantly increase the sensitivity of receiving equipment and as automated tracking systems become practical.

In the past, radio location of wild animals has been the primary focus of wildlife telemetry applications. I expect that physiologic telemetry will become increasingly important in the years ahead as we try to better understand the events and factors influencing wild animals. How far we progress will be a product of the quality of the questions asked and the technologies developed to meet the needs that arise.

Summary

Radio telemetry has provided tremendous benefits in our understanding of wild animals. These benefits can be enhanced by minimizing the disruptive aspects to the animals and by improving our own abilities and techniques in using radio telemetry equipment. Most important, however, is to start by identifying questions and then deciding whether or not radio telemetry could help provide better information than some other technique. If it can, we need to choose equipment that will provide the information we want with as few biases as practical. Radio telemetry is not amenable to all wild animal questions but it certainly has provided insights into animal behaviour, habitat use, and population processes which seemed unattainable a few years ago.

APPENDIX A

Glossary of Radio Telemetry Terms

Amplitude: Relative strength of an electronic or auditory signal; related to the degree of deviation of an oscillation from tne average.

Antenna: An electronically tuned device used to detect or transmit radio signals.

Attenuation: Decrease or reduction in the strength of a radio signal or an electrical impulse.

Azimuth: The compass bearing or direction (usually in degrees) to a point relative to some reference direction, frequently magnetic north.

Baseline: Straight line drawn between and extending beyond any two fixed signal receiving points.

Beacon: A radio transmitter that emits an unmodulated, but usually pulsed signal.

Bearing: Similar to azimuth. The direction, in terms of degree of arc, between a radio signal and some reference direction, frequently magnetic north.

Beat Frequency Oscillator (BFO): A reference radio frequency oscillator within a radio receiver used to convert signals at radio frequencies to lower frequency signals in the audible range.

BFO: Beat frequency oscillator (see above).

Coaxial cable: Special wires used to relay radio signals from antennas to receivers and other electronic equipment designed so that the ground conductor forms a continuous shield around the 'hot' lead, or conductor.

Decibel (db): A unit of measurement to describe the amplitude, or strength, of a radio signal.

Director: Any element in a yagi antenna placed in front of the driven element to increase the sensitivity of the antenna in the forward direction.

Driven element: The element in a yagi antenna to which the coaxial cable and tuning device are attached.

Frequency: One of the definitive characteristics of a radio signal determined by the number of complete oscillations of positive and negative phases per second.

Gain: Relative amplitude or volume of the output signal from an antenna, radio receiver, or other piece of electronic equipment.

Hybrid junction: A passive electronic device used to combine the output signals of two antennas or other pieces of electronic equipment into a common (single) signal.

In-phase: The coupling of two antennas in a 'sum mode' so that the positive phases and negative phases of incoming or outgoing signals reinforce each other in a common signal output.

Lead: Any of a variety of wires, coaxial cables, etc. used to connect pieces of electronic equipment to each other or to power supplies.

Megahertz (MHz): A frequency of 1,000,000 hertz, or cycles per second.

Null: The area(s) of the pattern of an antenna, or antenna array, which is totally insensitive to incoming or outgoing signals.

Oscillation: The regular alternations of a cyclic phenomenon (e.g. positive and negative phase alternations of a radio wave, alternating current, etc.)

Out-of-phase: Coupling of two antennas in a 'difference mode' so that the positive phase of one is cancelled by the negative phase of the other in the output signal.

Peak: The direction(s) or area(s) of the pattern of an antenna, or antenna array, from which a maximum signal is received or transmitted.

Radio receiver: An electronic device capable of detecting incoming signals at radio frequencies and converting them to another electrical output suitable to operate or trigger speakers, recorders, or other devices.

Radio transmitter: An electronic device used to generate a signal at radio frequencies.

Radio wave: One complete cycle of alternating positive and negative phases of electromagnetic energy at radio frequencies.

Reflector: An element placed behind the driven element in a yagi antenna to increase the sensitivity in the opposite direction.

Rose: A circular disc subdivided into equal divisions, usually degrees, and used to measure azimuths between incoming signals and known directions or points.

Shielding: Metallic outer conductor of coaxial cable designed to serve as the ground and to prevent radio signal intervention along the length of the 'hot' lead.

Stacking: Use of two or more antennas in a single array, coupled in-phase or out-of-phase to facilitate fixed-station telemetry techniques.

Transducer: A device that usually senses changes in electrical potential, resistance, or capacitance and is used to modulate or modify transmission characteristics of a transmitter.

Wavelength: The distance from a point on one wave to a comparable point on the preceding or succeeding wave.

Yagi: A type of antenna which utilizes three or more parallel elements in a straight line.

APPENDIX B

Sources for Wildlife Telemetry Equipment

Advanced Telemetry Systems, Inc.
23859 Northeast Highway 65
Bethel, MN 55005
Tel. (612) 434-5040

AVM Instrument Company
6575 Trinity Court
Dublin, CA 94566
Tel. (414) 829-5030

Cedar Creek Bioelectronics Lab
University of Minnesota
2660 Fawn Lake Drive NE
Bethel, MN 55005
Tel. (612) 434-7361

CompuCap
P.O. Box 864
Minneapolis, MN 55440
Tel. (612) 642-1368

Custom Electronics
2009 Silver Court West
Urbane, IL 61801
Tel. (217) 344-3460

Custom Telemetry and Consulting
185 Longview Drive
Athens, GA 30605
Tel. (404) 548-1024

Dev-Tron
400 Penn Ave. South
Minneapolis, MN 55405
Tel. (612) 377-7770

L. L. Electronics
P.O. Box 247
Mahomet, IL 61853
Tel. (217) 586-2132

Ocean Applied Research Corp.
10447 Roselle Street
San Diego, CA 92121
Tel. (619) 453-4013

Smith-Root, Inc.
14014 NE Salmon Creek Ave.
Vancouver, WA 98665
Tel. (206) 573-0202

Stuart Enterprises
P.O. Box 310
124 Cornish Court
Grass Valley, CA 95945
Tel. (916) 273-9188

Telemetry Systems, Inc.
P.O. Box 187
Mequon, WI 53092
Tel. (414) 241-8335

Telonics
932 East Impala Avenue
Mesa, AZ 85204-6699
Tel. (602) 892-4444

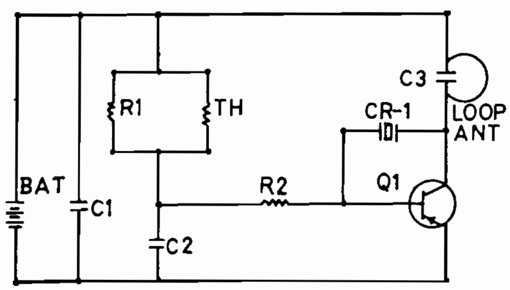
Vemco
R. R. No. 4
Armdale, Shad Bay
Halifax County, Nova Scotia
Canada B3L 4J4
Tel. (902) 852-3047

Wildlife Materials, Inc.
R. R. 3
Glant City Road
Carbondale, IL 62901
Tel. (618) 549-6330

Note: This list is not exhaustive but indicative and does not imply any endorsement.

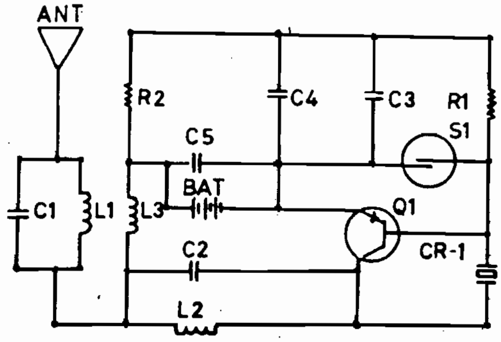
APPENDIX C

Electronic Schematics for Several Simple Transmitters and a Receiver



Component	Description
CR–1	Crystal (selected for frequency)
R1	Resistor, 68 to 180 K-ohm
C1	Capacitor, 100 to 180 pF (selected for correct channel frequency)
C2	Capacitor, 0.01 μF (selected for 0.2 mA current drain)
Q1	Transistor, NPN (Motorola MMT 2369)
RFC	Radio frequency choke (22 turns of AWG No. 38, wound on a 1/8 watt resistor form)
BAT	Battery, 16 to 40 mah

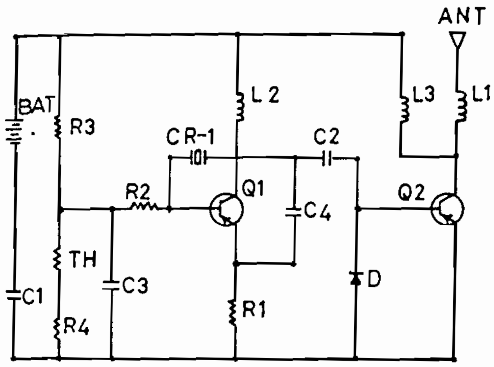
FIGURE C-1. Schematic and parts list for a simple, light-weight (1.1 to 1.4 gram) 30 MHz radio transmitter suitable for short duration studies of small rodents (From Kolz, *et al.* 1972)



Component	Description
ANT	Antenna, 4.38–35 cm length
C1	Capacitor, 24–30 pF, HIQ Type ceramic
C2	Capacitor, 18–50 pF, HIQ Type ceramic
C3, C5	Capacitor, 0.01 μF, ceramic
C4	Capacitor, 10–30 μF, tantalum electrolytic
L1	Coil, 1.5 T #28 on 470 K-ohm, 1/4W
L2	Coil, rf choke, 0.8–1.2 uH, moulded
L3	Coil, 3.5 T #28 on 1 M-ohm, 1/4W
Q1	Transistor, 2N2369A, B ≥ 80
R1	Resistor, 2 K-ohm, 1/4 watt
R2	Resistor, 75–120 K-ohm, 1/4 watt
S1	Magentic reed switch, NO
CR–1	Crystal—divide desired frequency by 3 and, order HC/18 holder with wire (pigtail) leads, 3rd OT, 1–2 MW ± 0.002% tol, series resonance (i.e. 164.436÷3 = 54.812 MHz)

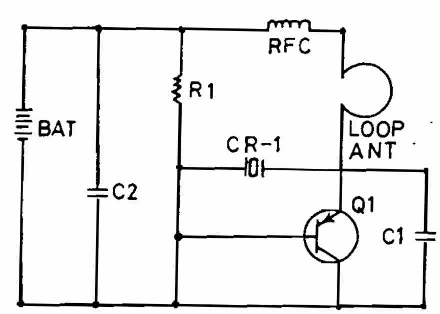
Note: (a) adjust C1L2 for resonance with antenna length involved; (b) adjust C2 for pulse width; (c) adjust C4R2 for pulse rate.

FIGURE C-2. Schematic and parts list for a simple but effective radio transmitter that can be built with relatively little knowledge of electronics (From Dodge 1982)



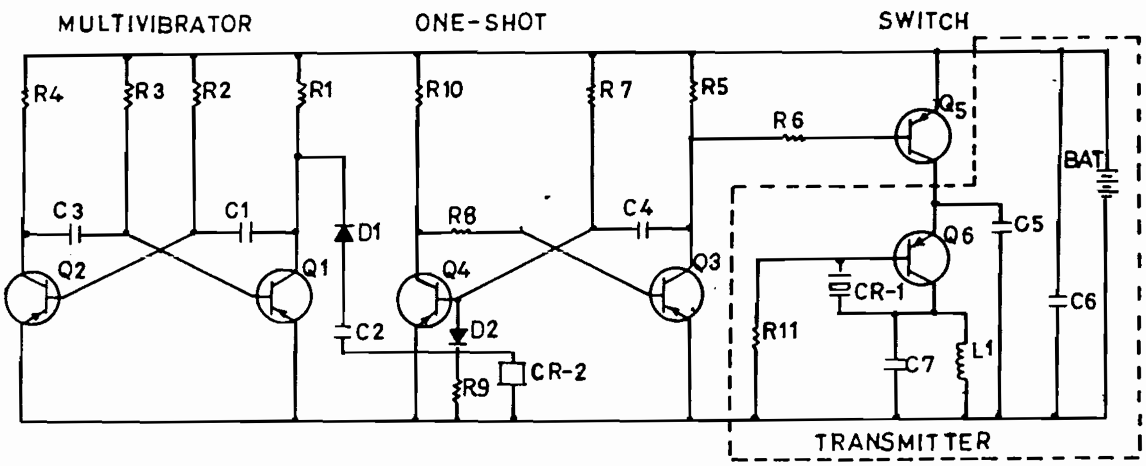
Component	Description
R1	Resistor, 1/8 W, 68 to 100 ohms
R2	Resistor, 1/8 W, 1.5 to 3.3 K-ohms
R3	Resistor, 1/8 W, 120 to 220 K-ohms
R4	Resistor, 1/8 W, 82 K-ohms
C1, C2	Capacitor, 0.033 μF, chip
C3	Capacitor, 4.7 to 10 μF, tantalum
C4	Capacitor, NPO, 12 pF, chip
Q1, Q2	Transistor, MMT 3014 (Motorola, Inc.)
D	Diode, MMD 6050 (Motorola, Inc.)
TH	Thermistor, PA51D1 (Fenwall Electronics)
CR-1	Frequency crystal (Erle Technological Products)
L1, L2, L3	Coils of 4, 12, and 5 turns, respectively, AWG 36, 1/8-in diameter, Ferrite core-13 material (Permacor)
ANT	Antenna, spring steel music wire, 11 3/4" length, 0.0157" diameter

FIGURE C-3. Schematic and parts list for a light-weight 160 MHz transmitter for birds and bats (From Kolz and Corner 1975)



Component	Description
BAT	Battery, two mercury E-1's
C1	Capacitor, 0.005 mF ceramic
C2	Capacitor, 10 MF electrolytic
C3	Capacitor, 25–280 mmF, ceramic trimmer
R1	Resistor, 1 M-ohm 1/4 watt
R2	Resistor, 580 ohm, wire wound Sprague
TH	Thermistor, 1 M-ohm, Fenwal glass bead
CR-1	Crystal, miniature, 50 MHz Tex. Instr.
Q1	Transistor, NPN, 834 Motorola

FIGURE C-4. Schematic and parts list for a simple mortality indicating transmitter utilizing a thermistor to change the transmission rate with a change in temperature associated with loss of body heat (L.C. Stoddart, pers. comm.)



Component	Description	Component	Description
Q1, Q2, Q3, Q4	Transistor, Gen. Elect. 2N3391A	R2, R3, R7	Resistor, 10 M-ohm, 1/10W
Q5, Q6	Transistor, Tex. Instr, 2N711B	R5, R9, R10	Resistor, 330 K-ohm, 1/10W
C1, C3	Capacitor, 0.47 µF/20v.	R6	Resistor, 15 K-ohm, 1/10W
C4	Capacitor, 0.22 µF/20v.	R8	Resistor, 1 M-ohm, 1/10W
C2, C5	Capacitor, 0.001 µF/20v.	R11	Resistor, 47 K-ohm, 1/10W
C6	Capacitor, 68 µF/20v.	CR-1	Crystal (selected for frequency)
D1, D2	Diode, Fairchild FDM-6000	CR-2	Motion tranducer (fabricated from Sonotone 2TA-S cartridge)
R1, R4	Resistor, 2.2. M-ohm, 1/10W	ANT	Antenna

Note: (a) Adjust R2C1 and R3C3 for repetition rate, increase RC for longer time between pulses; (b) Increase R7C4 for longer 'on' time; and (c) C7 selected to tune L1 to resonant frequency.

FIGURE C-5. Schematic and parts list for a radio transmitter which uses a piezoelectric element (part CR-2) as a motion detector to provide extraneous radio transmissions with each significant movement of the transmitter (from Knowlton, *et al.* 1968)

PARTS LIST FOR THE 26-27 MHz MODEL D-11 (See Figure C-6)

Component	Description
B1	Battery, 1.5 volt
B2	Battery, 9.0-volt transistor
C1	Capacitor, 0.001 mF, disc
C2	Capacitor, 50 pF, silver mica
C3	Capacitor, 43 pF, silver mica
C4	Capacitor, 5 pF, silver mica
C5	Capacitor, 120 pF, silver mica
C6	Capacitor, 150 pF, ceramic, N750
C7	Capacitor, 510 pF, silver mica
C8, C9, C20	Capacitor, 20 mF, electrolytic, 15 vdc
C10, C11, C12	Capacitor, 0.05 mF, disc ceramic, 50 vdc
C13	Capacitor, 0.1 mF, disc ceramic, 50 vdc
C14–C19	Capacitor, 0.01 mF, disc ceramic, 50 vdc
R1–R20	Resistora, 10 K-ohm, 1/2 W, 10% tol.
R21, R37	Potentiometer, 10 K-ohm
R22	Resistor, 33 K-ohm, 1/2 W, 10% tol

Component	Description
R25, R26, R29, R31, R32, R39, R43	Resistors, 1 K-ohm, 1/2 W, 10% tol
R27	Potentiometer, 100 K-ohm
R28, R30, R36	Resistors, 2.7 K-ohm, 1/2 W, 10% tol.
R23, R24	Resistors, 100 K-ohm, 1/2 W, 10% tol.
R33, R34	Resistors, 100 K-ohm, 1/2 W, 10% tol.
R35, R38, R40	Resistors, 4.7 K-ohm, 1/2 W, 10% tol.
R41	Resistors, 820 ohms, 1/2 W, 10% tol.
R44	Potentiometer, 75 K-ohms
Q1, Q2, Q3	Transistors, 2N1742
Q4	Transistor, Philco T2028 or 2N1225
Q5, Q6	Transistors, 2N404, SYL108, or 2N270
CR-1	Crystal, third overtone
D1	Varactor diode, Hughs IN754
D2	Zener diode, 6.8 V, IN754

Component	Description	Component	Description
P1	Mercury cell, 1.35V, E-9 or equivalent	S2	11 pos, 2 deck, rotary switch
P2	Mercury cell, 8.4V, E-146 or equivalent	S3	SPDT, slide switch
L4	Torold, 88 mhy, centre tapped	P1	BNC receptacle, female (for antenna lead)
S1	DPDT toggle switch	P2	Receptacle for earphone jack

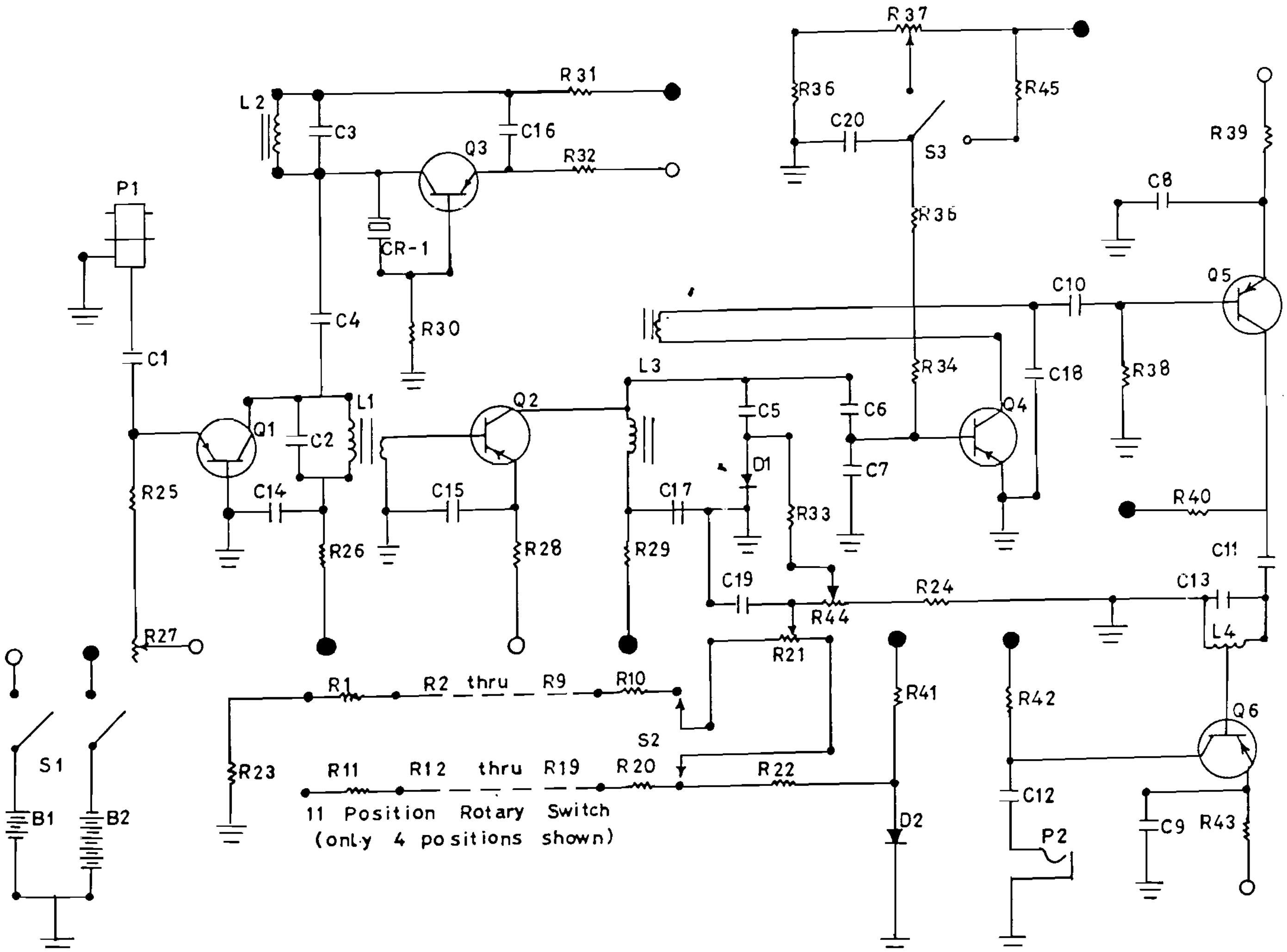


FIGURE C-6. Schematic and parts list for a simple telemetry receiver (model D-11) which can be built with a modest knowledge of electronics (from Cochran and Nelson 1963)

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